Mock loop

Amsterdam UMC

Wednesday 19th October, 2022

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1 Mock loop overview

We have built a double mock circulation setup in the AMC, where it will be located for the duration of this project.

This mock loop setup accurately mimics the cardiovascular system of a human body including the pulmonary and systemic circulation. The mock loop is used to perform in vitro-tests of the Hybrid Heart prototypes while working in physiological and pathological conditions (when preferred).

The set up works in such way that “the blood” is pumped by the Hybrid Heart prototypes into both circulations. We mimic the viscosity of the blood with water and glycerol. From the right ventricle of the Hybrid Heart the “blood” is pumped in the pulmonary circulation of the mock loop setup. To mimic the physiological pulmonary circulation, we set an afterload (Pulmonic blood pressure) and set on a peripheral resistance the pulmonary resistance to balance the pressures between the pulmonary preload and afterload. After passing the pulmonary resistance, the “blood” enters the preload tack, which is set on a filling pressure which is to mimic the left atrium. “Blood” is then ejected by the HH left ventricle into the “systemic circulation” with an afterload that is set to the mean aortic blood pressure and a peripheral resistance according to the systemic resistance in the body. “Blood” will thereafter continue to the right atrium, which has a fills the right ventricle.

To actuate the pneumatic driven Hybrid Heart we have also incorporated a pneumatic circuit into the mock loop. This network is used to control and measure the actuation of the Hybrid Heart in different scenarios. We are able to accurately control the driving pressure and air flow timings to perform tests at different beat rates and working pressures, as well as measure the amount of air required by the Hybrid Heart to “pump”. Thereby, giving us the efficiency of our heart and perform suitable optimizations in further prototypes.

1.1 Technical specifications

1.1.1 Mock loop

To be able to precisely test the workings of the Hybrid Heart various sensors are fitted to the mock loop to measure different parameters relating to the output of the Hybrid Heart. We also have components to be able to control the mock loop and set the appropriate conditions required for physiological flow.

1. Tubing: Tygon Tubing are used as tubes as they provide low resistance to the flow of blood.They have an inner diameter of 25mm and outer diameter of 30 mm.

2. Compliance Chambers: The compliance chambers are present to passively mimic the rise and fall of the blood pressure in the aorta. This is representative of the ability of the blood vessel to expand and contract due to its own elasticity.

   The compliance is split into two parts the systemic and pulmonary afterload and preload. The afterload compliance is emulated by closed air chambers. The pressure in the compliance chambers increases based on the flow rate generated. The compliance value is determined by the volume of air present in the chamber. By filling the chambers with water and by sealing them we can set the amount of air volume in the chambers to achieve required compliance values. The compliance allows the pressure in afterload to increase by a specified amount (eg 70mmHg to 120mmHg). If the compliance is not set correctly the pressure in the afterload may be higher or lower than the required amount even if the stroke volume is in physilogical range. The preload compliance are emulated by open air chambers and their compliance values are based on the geometry of the chambers.

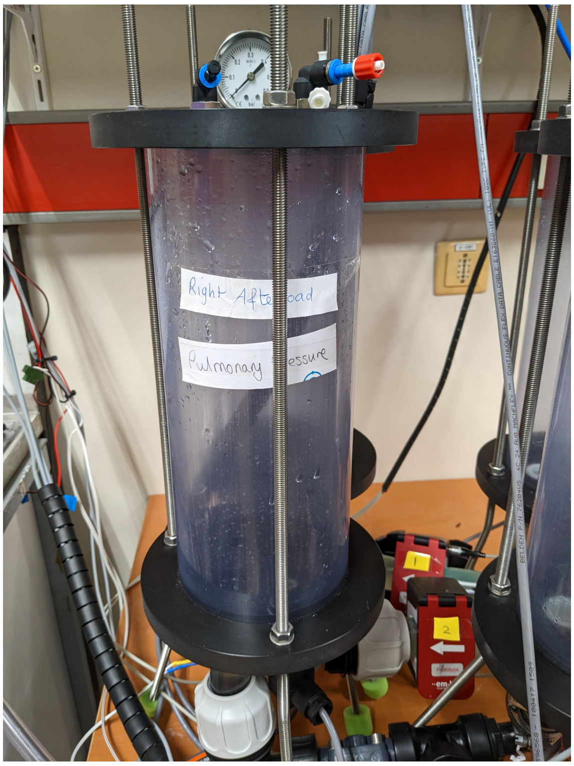

Figure 1.1: A single closed compliance chamber

In construction the chambers are 120mm in diameter and 30mm high. The inflow and outflow connections along with the the pressure sensor are mounted at the bottom of the chambers. Regular pipe fittings are used as connectors. Each pair of chambers also has a port with a electronically connected solenoid valve for easy filling of the system. The ports at the top of the chambers allows the chambers to be sealed to atmosphere and can be unsealed to drain out the water.

3. Flow resistors: The resistor used is a Burkert diaphragm pinch valve. The resistor offers obstruction to the flow of "blood". It is used to set the pressure difference between the afterload chamber and the preload chamber it is connected to.

2 Sensors

2.1 Pressure Sensors

Pressure sensors are placed across the cardiovascular network to monitor the different pressure changes in the system. We are able to measure the pressure changes in the afterload(aortic and pulmonic pressure), preload(atrium) and ventricular pressures. OsiSem XM XMLP500MC11F Electronic Pressure sensors were used. Which are rated at 0.5 V to 4.5V and can measure pressures from 0 to 500 mbar.

Figure 2.1: XMLP500MC11F Pressure Sensor

Pin	Description
Pin 1	Power supply +5v
Pin 2	Analog output 0.5 - 4.5v
Pin 3	GND
Pin 4	Shielding

Table 2.1: Pin Configuration

2.2 Liquid/blood low sensors

Ultrasonic clamp-on liquid flow sensors from em-tec are used to measure the output flow of the heart to measure the cardiac output. We are able to accurately calculate the stoke volume during each beat and calculate the amount of blood pumped by the heart.

Figure 2.2: Ultrasonic flow sensor

Each of the flow sensors are connected to a DIGIFLOW-EXT1 flow measurement board which measures the signal from the flow sensors and provides and analogue output in the range of 0 to 5V and can measure upto 32L/min. The flow sensors were tested and validated before use. The board provides analogue output at different frequencies at 100Hz, 10Hz and 1Hz. To maximize our data points the 100Hz output was used.

Figure 2.3: DIGIFLOW-EXT1 board.

Power input	24V
Pin 18	Analog output 100Hz
Pin 19	Analog output 10Hz
Pin 20	Analog output 1Hz
Pin 6	System GND

Table 2.2: Pin Configuration

2.3 Air flow Sensor

We also measure the volume of air into and out of the actuators. Measuring the driveline pressure and volume in and out of the heart we can better optimize the heart. Two festo air flow sensors (SFAH-100U-Q8S-PNLK-PNVBA-M8) with range 2 - 100 L/min were used one on the positive pressure side and one just before the vacuum generator. This gives us an accurate measurement of air flowing to the actuator and the amount of air removed from the actuator.

Figure 2.4: Festo Air flow sensor

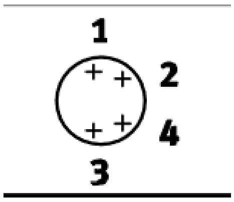

Figure 2.5: Connection Diagram

Pin No.	Color	Assignment
1	Brown	+24 V DC
2	White	Analogue output
3	Blue	GND
4	Black	IO link

Table 2.3: Pin Configuration

3 Control unit

3.1 Data Acquisition

A NI 6343 DAQ was used as the control board of the system. It has 32 analogue input ports for monitoring the different sensors. Two analogue outputs provide control to the electronic pressure regulator and many digital output pins for controlling different parts of the system. The data is acquired through a HybridHeart labview based app which can control the various output ports and store the various inputs in a readable file.

Figure 3.1: NI-6343 DAQ board

3.2 High Voltage/Current switching circuit

Various 3/2 solenoid valves are used throughout the system from controlling the timing of the pneumatic line to controlling the filling and draining of the compliance chambers. These are controlled through the digital ports of the DAQ board by a high power switching circuit using MOSFETs as shown in Fig.3.4.

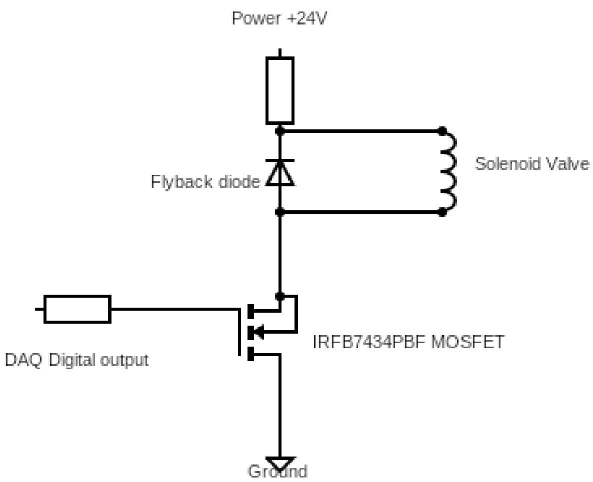

Figure 3.2: MOSFET high voltage switching circuit.

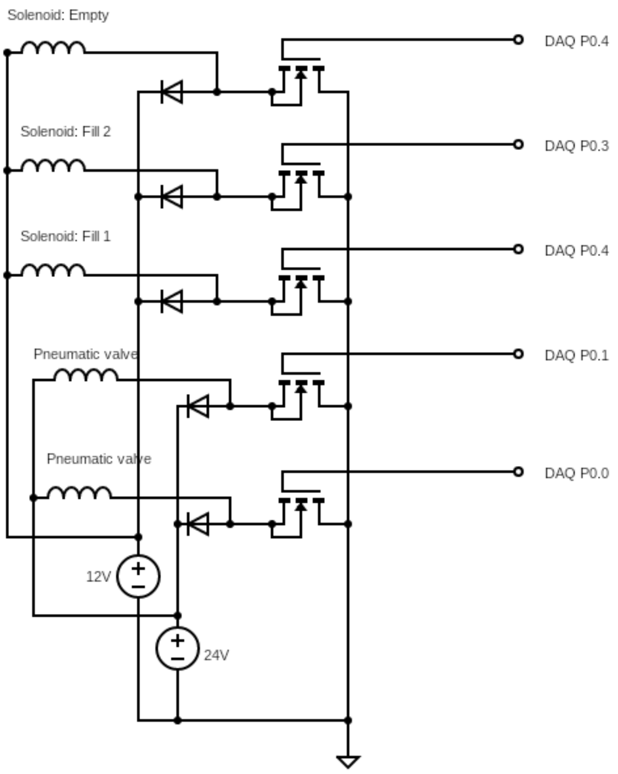

Figure 3.3: MOSFET solenoid control circuit.

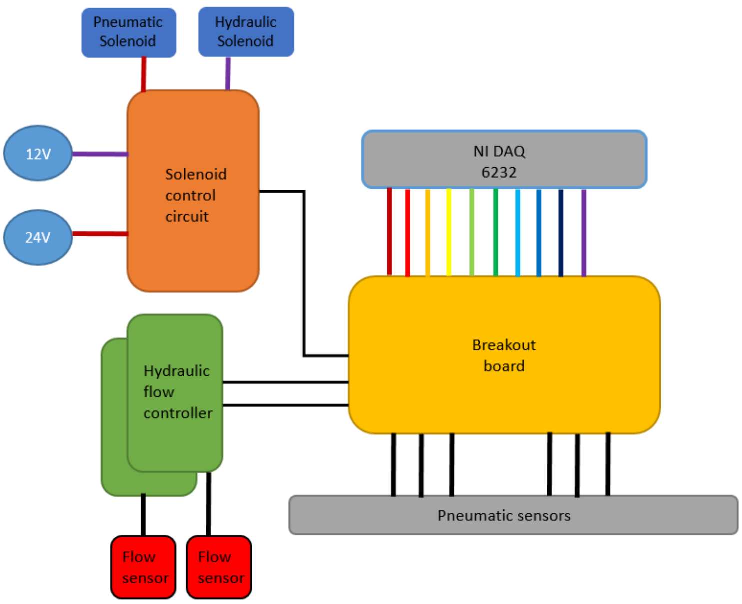

Figure 3.4: Schematic of electrical system.

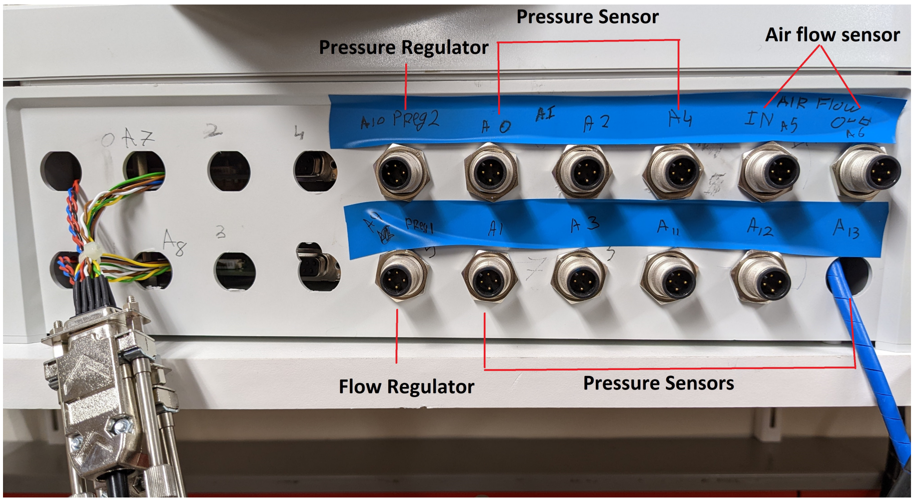

Figure 3.5: Front end of controller box for sensors.

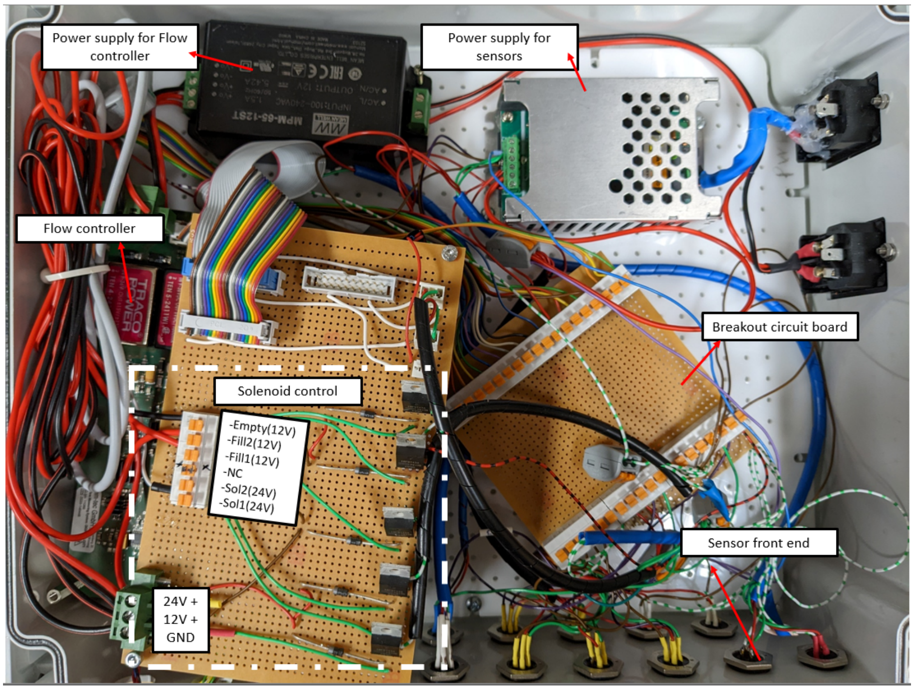

Figure 3.6: Internals of controller box.

A/I 0	A/I 1	A/I 2	A/I 3	A/I 4	A/I 5	A/I 6	A/I 7	A/I 8	A/I 9	A/I 10	A/I 11	A/I 12	P0.2	P0.1	P0.0	GND
Psen1	Psen2	Psen3	Psen4	Psen5	AirFlow Sen1	Airflow Sen2	HFlow1	HFlow2	AirFlow ctrl A/O	AirFlow ctrl Setpoint	Psen6	Psen7	Solenoid Fill	24V Solenoid2	24V Solenoid1	GND

Table 3.1: Break out board connection sequence.

4 Pneumatic system

The pneumatic network is used to actively control and monitor the driving side of the hybrid heart. We can control the driving pressure and the timing of each "beat". The pneumatic circuit consists of the following:

4.1 Pressure regulator

Depending on the various pressures across the system we have different pressure regualtors to accurately control the pressure through the system

- Manual pressure regulator 1: 0 - 10 bar Pressure regulator MS4-LR-1/4-D6 from festo to provide enopugh pressure for the working of the high pressure driveline.
- Electronic Pressure regulator: 0 to 2 bar electronic pressure regulator from Festo (VPPE-3-1-1/8-2-010-E1) to accurately control the pressure to the hybrid heart. This was chosen for its high flow rate.

Figure 4.1: Festo electronic pressure regulator

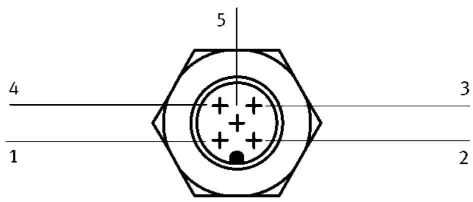

Figure 4.2: Connection Diagram

Pin No.	Color	Assignment
1	Brown	+24 V DC
2	White	Analogue input '-' setpoint value
3	Blue	GND
4	Black	Analogue input '+' setpoint value (0 - 10 V)
5	Grey	analogue output (0 - 10 V)

Table 4.1: Port Configuration

4.2 Vacuum Generator

For quickly removing the air from the actuators inside the hybrid heart we have included a vacuum generator to actively pump out the volume of air. The vacuum generator is fropm Festo (VN-14-L-T4-PQ2-VQ3-RO2) and is based on a venturi design where the driving pressure of upto 8 bars generates a maximum suction rate of 90L/min.

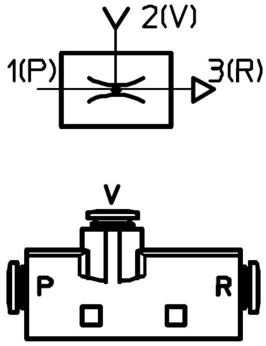

Figure 4.3: Festo vacuum generator

Port	Description
Port 1	Input port upto 8 Bars
Port 2	Vacuum port
Port 3	Exhaust port

Table 4.2: Vacuum generator connection ports

4.3 5/2 Solenoid valve

Festo MHE2-MS1H–5/2-QS-4-K solenoid valves were used to control the actuation of the hybridheart. Two 24V 5/2 valves are connected in parallel such that they work together to allow the actuator to be either connected to the pressure supply or by default be connected to the vacuum generator. The actuator by default is connected to the vacuum generator through the solenoid valves to prevent the actuator from exploding in case of an emergency. On signal from the NI DAQ the solenoids actuate and the actuator is connected to the pressure regulator to fill up the actuator to a set pressure. The timing of these valves set the systole and diastole time.

Figure 4.4: Festo pneumatic 5/2 Solenoid valve

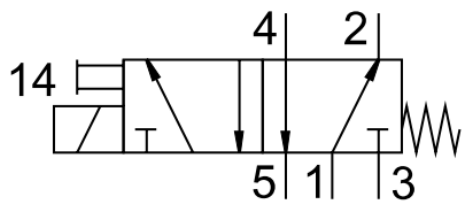

Figure 4.5: Schemtic of valve

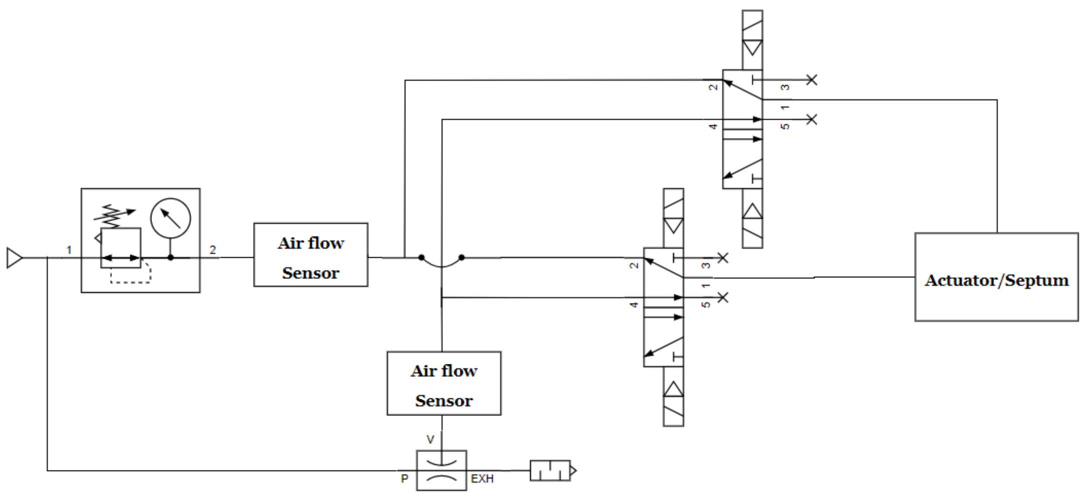

Figure 4.6: Pneumatic circuit to control the Hybrid Heart

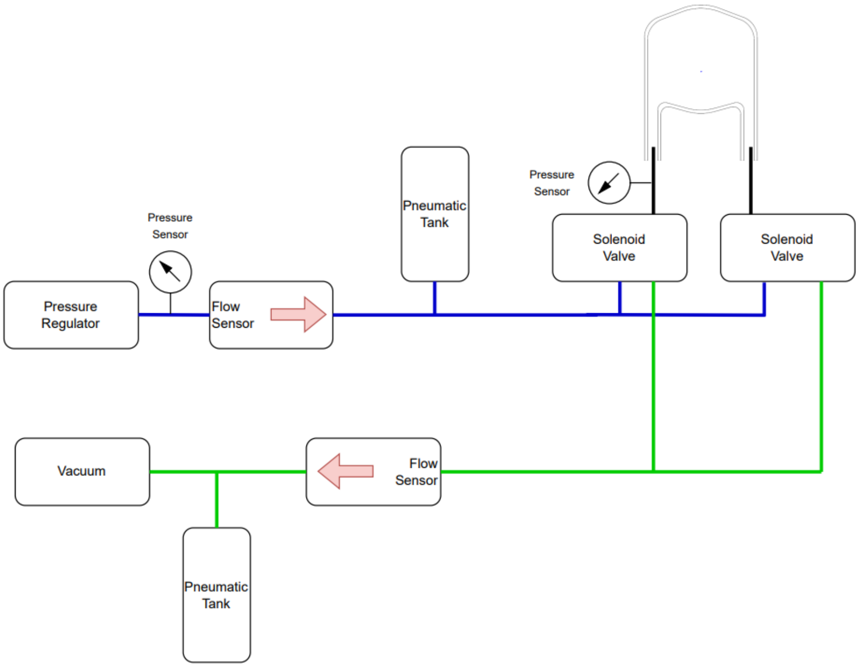

Figure 4.7: Simple schematic of pneumatic circuit.

4.4 Mass flow controller

There is also provision for an extra mass flow controller from festo (VEMD-L-6-14-20-D21-M5-1-R1-V4). It can be used to control the flow rate to the system.

Figure 4.8: Festo electronic flow regulator

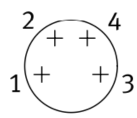

Figure 4.9: Connection Diagram

Pin No.	Color	Assignment
1	Brown	+24 V DC
2	White	Setpoint value 0.2 - 10V
3	Blue	GND
4	Black	Actual value 0.2 - 10V

Table 4.3: Port Configuration

5 Data acquisition

For data acquisition we currently use the HybridHeart App, which is a Labview based app. The sensors are connected to the NI-6343 controller and the corresponding ports are configured in the HH app. Each sensor can also be calibrated according to their respective data sheets and their conversion formulae are put into the app before starting any experiment.

The data is then stored in a text file with all selected sensors data being stored in columns in the text file. The data is then read through a matlab script which generates the plots for the pressures and flows respectively.

5.1 Sensor Configuration

1. Pressure Sensor
   - Sensor Range : 0 - 375 mmHg
   - Voltage range (V) : 0.5 - 4.5 V
   - Calibration Expression :Pressure = $(V-0.5)*\frac{375}{4}$
2. Hydraulic flow sensor
   - Sensor Range : 0 - 32 L/min
   - Voltage range (V): 0 - 5 V
   - Calibration Expression :Flow rate = $\frac{V*32}{5}$
3. Air flow sensor
   - Sensor Range : 0 - 100 SLPM
   - Voltage range (V): 0 - 10 V
   - Calibration Expression :Flow rate = $\frac{V*100}{10}$
4. Festo VPPE pressure regulator
   - Sensor Range : 0 - 2 Bar
   - Voltage range (V): 0 - 10 V
   - Calibration Expression :Pressure = $(V-0.1)*\frac{1.98}{9.9}+0.02$
5. Festo Mass flow controller
   - Sensor Range : 0 - 20 L/min
   - Voltage range (V): 0 - 10 V
   - Calibration Expression :Pressure = $\frac{(20*V-4)}{9.8}$

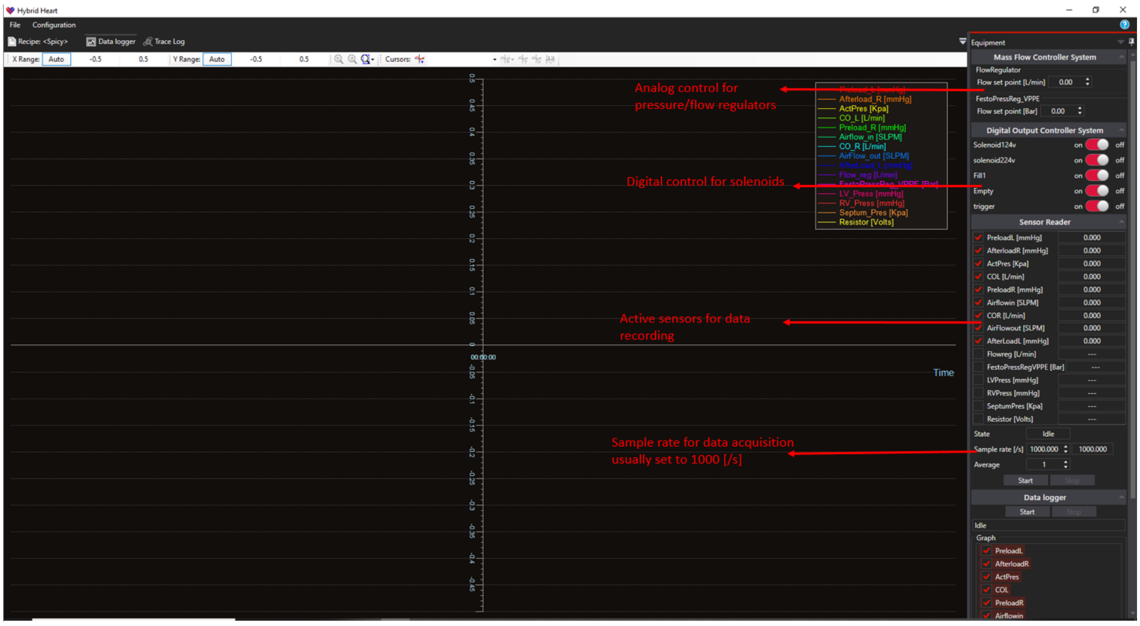

Figure 5.1: Front end of GUI of HybridHeart app

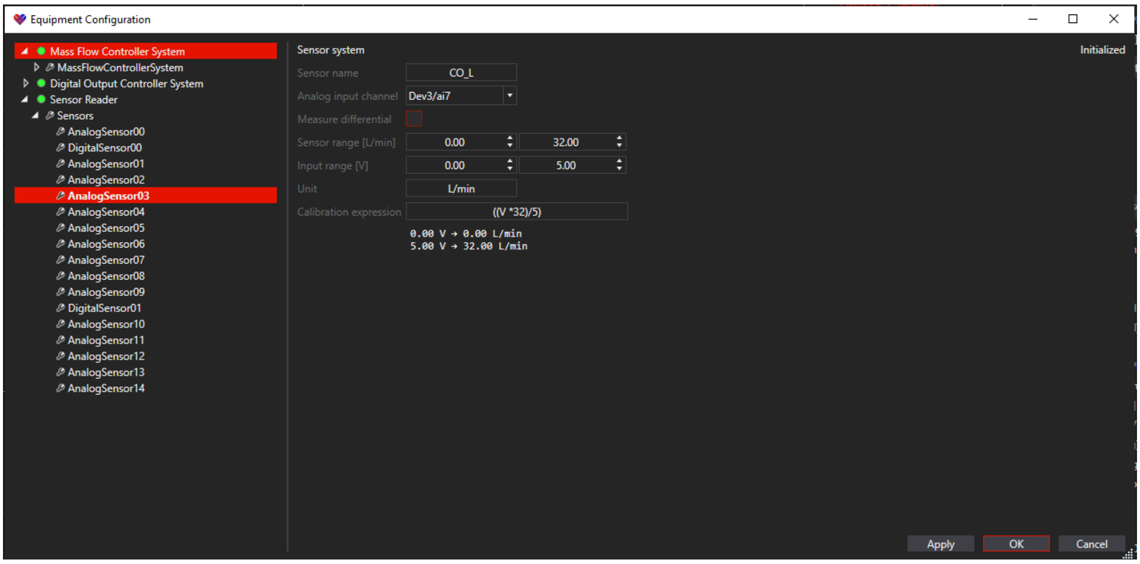

Figure 5.2: Example of configuring analog input 7 to measure the left flow volume.

6 Power Requirements

The entire mock loop system contains 5 total power supplies for the different connected devices and sensors.

1. TPP 65-3512
   Contains 3 DC outputs for 24V, 5V and 12V with current rating of 1.5A, 6A and 0.6A respectively. This supply is used to power the pressure sensors and other basic sensors that need to be connected to the system.

2. MPM-6512ST
   A 12V 5.42A power supply used to power the EM-Tec flow sensors. Can be used to connected upto 4 flow sensor boards.

   Note: The ground of this system is required to be isolated from the rest of the system.

3. SRS-150-24
   A 24V 6.5A power supply for powering the festo 24V Solenoids.

4. Wall adapter
   A 12V 1.5A wall adapter for powering the general use 12V Solenoids. Cannot be used to power multiple solenoids at a time. An upgraded power supply with higher current is needed to run more than one simultaneously. Currently they are used to power the solenoid to fill and empty the mock loop.

No.	Product	Purpose	Quantity	Required voltage	Maximum power (each)	Available power	Power supply
1	XMLP500MC11F	Pressure Sensor 0 - 0.5 Bar	6	5V	0.1W	24/5/12 VDC 1.5/6/0.6 A (65W)	TPP 65-3512
2	XLMP2D5GC11F	Pressure Sesnor 0 - 2.5 Bar	2	5V	0.1W		
3	VPPE-3-1-1/8-2-010-E1	Pressure Regulator	1	24V	1W		
4	VEMD-L-6-14-20-D21-M5-1-R1-V4	Mass flow controller	1	24V	1W		
5	SFAH-100U-Q8S-PNLK-PNVBA-M8	Air flow sensor	2	24V	0.25W		
6	Digiflow ext Ultrasonic flow sensor	Hydraulic flow sensor	2	12V	7W	5.42A (65W)	MPM-6512ST
7	MHE2-MS1H--5/2-QS-4-K	Pneumatic 5/2 Solenoid valve	2	24V	6.5W	(156W)	SRS-150-24
8	12V solenoid	Hydraulic one way Solenoid valve	3	12V	2W	12VDC 1.5A (18W)	Wall adapter
9	USB 6343	USB Data acquisiton device	1	12V	30W	12VDC 3A (36W)	Provided wall adapter

Figure 6.1: Power supply requirements

7 Startup Procedure

This section will describe the basic startup of the mock, which includes the filling of the loop along with how to run the heart using the pneumatic's mentioned in chapter 4.

1. First and foremost the heart is to be attached to the mock loop. The general configuration is that the inflow valves are placed lower to the outflow valves. This is to allow easy removal of air from ventricles.

2. Make sure all chambers are open to air.

3. Turn on the power rail of the control unit. Power can be seen on the DAQ board, 2 switches on the side of the controller box, lights on the flow controller board and the pneumatic sensors and regulator screens.

4. Using the HHapp mentioned in chapter 5 use the "Fill" button to control the solenoid which will fill the mock loop. The other end is connected to either the tap or a tank. Fill the mock loop to about 7mmHg pressure in all the 4 compliance chambers. This water level is required by the afterload chambers to have around 2.5ml/mmHg compliance. Once the water level in the afterload is set close the afterload chambers from air. The water level in the afterloads will no longer change and we can adjust the preload pressures as required.

5. Open the HHRunapp matlab app which is specifically designed to run one solenoid (both 24V solenoids are connected together) connected to P0.0 digital o/p of the DAQ and control the A0 analog o/p of the DAQ. In the app we can set the pressure in the regulator and the number of cycles and HR and systole time for the beats which is produced by the opening and closing of the solenoid valve.

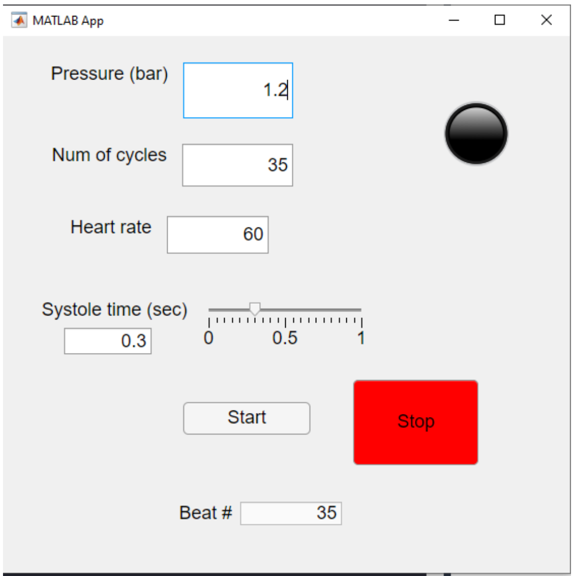

Figure 7.1: GUI for HHRunapp made in matlab

- The systole time bar adjusts based on HR.
- The stop button turns off the solenoid which by default connects to the vacuum for safety.

6. Once the heart starts running the pressure in the left afterload will begin to rise till it reaches steady state. To increase the pressure tighten the resistor and open it to reduce the pressure.

7. The data is saved by the HHapp and needs to be running to capture data. The sample rate is usually set to 1000 samples/sec.

8. In the command script for the HHapp write a wait function which looks like ’wait x min’ or ’wait y sec’ to run the data recording for x or y amount. Make sure to specify the output folder where the data should be stored.

9. To empty the mock loop a solenoid is fitted to the bottom of the right afterload chamber which will allow the flow of water based on gravity to exit the mock.
   - Additional measures might be needed to fully empty the mock.
   - Pressurizing the chambers or applying vacuum to the right afterload will allow water to collect in it for emptying.
   - The heart can be removed to completely empty the loop.

10. If not in use turn off the power to the flow boards. Disconnecting the entire power rail will cause all apps to stop working and will need to be restarted.